Comparative Study of Optical and RF Communication Systems for a Mars Mission
Part II. Unified Value Metrics

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ABSTRACT

In this Part-I I report of the Advanced Communications Benefits study, two critical metrics for comparing the benefits of utilizing X-band, Ka-band and Optical frequencies for supporting generic classes of Martian exploration missions have been evaluated. The first of these is the overall equivalent communications system mass on the spacecraft. The second comparison metric is the overall cost impact. This "overall" cost assessment has considered the costs for both the spacecraft end of the link and the ground end. In both cam the metrics indicate that higher frequency communication bands have favorable mass and cost, particularly at higher data volumes transmitted daily to the earth. The same metrics are also applied to telecommunication for a hypothetical Neptune mission, extrapolating from the designs for the Mars case.

1. IN TRODU CTION

in Part-1 of this report [1], we presented the individual technical and cost characteristics for telecommunications architectures at three different communication bands. The X-hand, Ka-band and Optical frequencies, each capable of delivering a range of da(a transport from O. 1 to 10.0 Gbits/day from Mars were considered, We attempted to adjust the design parameters for each system so that comparisons were being made between systems of equal overall performance. The results of that work are believed to be the right elements for developing design trades for potential future missions. Nevertheless, it is often useful to develop a combined/unified value metric when considering what technology areas should be given emphasis or applied to a general class of future missions. In Part-Ii of this report we attempted to develop two such metrics: (1) the aggregate spacecraft mass; and (2) the aggregate spacecraft cost. The metrics are used to explore the impact of some of the assumptions made in this study.

2. AGGREGATE SPACECRAFT MASS METRIC

One of the most critically limited resources in the design of a spacecraft is the ziggm.gate mass of the flight subsystems. The aggregate spacecraft telecom-related mass is the sum of the estimated mass of the telecom subsystem for each of the configurations plus the cross-impact on the mass of other subsystems, for example, the effect of higher mass for the terminal on the power subsystem.

A baseline of 0.10 precision for spacecraft orientation is assumed for all telecom designs so that the telecom subsystem will have no impact on the attitude control subsystem. Where higher precision is needed, the telecom subsystems provide higher precision themselves. Power, however, does wiry for each of the.w designs and thus the cross-impact of the telecom power requirements upon the mass of the power subsystem becomes a part of the unified mass metric. For a Mars orbiter, the power subsystem consists of a solar array, plus a battery to carry operation through the eclipse periods while the spacecraft is in Mars shadow, plus power conditioning and distribution components. The capacity of the solar array must provide for both telecom operations and charging of the battery through the sun-lit periods. Since the telecom impact is being considered in isolation, there is no provision in this study to account for any power savings due to power budget sharing with other subsystems. The sensitivity to possible power budget saving will be explored later using Metric #2. The results of this sub-study of the power subsystem cross-impacts appear in the Ref. [2]. For each user Watt, 2. I W of solar array power must be available, which would occupy 0. 14 kg. Adding the required battery (0.8 W-h) brings the total crow impact to 0.17 kg per user-Watt.

Figure (1) shows the aggregate telecom-related mass for the nine configurations considered (three different frequencies and three different data volumes). When viewed in this form, the advantage of the new higher frequency technologies is evident, as the aggregate spacecraft telecom-related mass is monotone decreasing with transmission frequency. The expected advantage is modest at the lowest data volume, but increases with data volume. It becomes very significant at the 10.0 Gb/day, Where the Ka-band mass metric is about 3/4 of that for X-band and the Optical mass metric is about half of X-band and 2/3 of Ka-band.

3. AGGREGATE TELECOM COS T METRIC

Overall cost of fulfilling the telecom needs of a mission includes terms for:

(1) Cost of development of the flight telecom equipment, including the cross-impacts onto the ***power*** subsystem (and possibly others);
(2) Cost of transportation of the flight equipment mass to the destination planet;
(3) Cost of development or upgrade to the ground telecom terminal equipment; and
(4) Cost of maintaining and operating that equipment for the time interval applicable to the mission.

Specific cost estimates for development of the flight and ground telecom terminals were developed along with the technical designs which are described in Part-1 of this report. [1] Cross-impact on the mass of the power subsystem is discussed above. Costing rationale for the power, transportation and operations cost terms were developed and tested against a variety of available sources. [2-6] Cost of transporting a payload to Mars orbit depends upon a variety of factors, including among other things what one assumes to be the launch vehicle, and what other terms one might choose to book-keep with the launch vehicle. The figure used in our study is consistent with Mars Observer Spacecraft experience, and with forecasts for developmental light duty launch vehicles.

Cost of operation and sustaining of the optical ground telecom terminal was estimated along with its technical design using the assumption that the new terminals would be fully automated in their operation. Cost of operating and sustaining the DSN (NASA's Deep Space Network) for an additional user can be taken to be equivalent to the hourly price set for reimbursable users. [6] This figure of course is consistent with the way in which the DSN currently operates and would be different if the Network were to become fully automated. Efforts are underway to reduce this figure significantly, perhaps cutting cost per service-hour by as much as half. For both types of terminals, the chargeable cost per service-hour accumulated over the expected annual number of user service-hours turns out to fall in the range of 4% to 8% of the net current capital value of the terminals.

3.1 Aggregate telecom Costs & Sensitivities

We have chosen to display cost figures not in actual dollars but in units normalized by the initial development cost of a small X-band flight terminal. The (normalized) development costs of the various flight and ground terminals appear in the summary, Section IV. of our earlier report [2] and are repeated here:

Comparison of the Three Communication Systems at Three Different Data Volumes

Data Volume (Gb/day)	Communication Band	Mass (kg)	D.C. Power (W)	Cost ($ M) (first unit)
	X-Band	16.5	15.4	10.1
0.1	Ka-Band	11.1	15.8	10.9

	Optical	6.4	19.9	14.3
1.0	X-Band	16.7	29	10.5
	Ka-Band	11.3	32	12.3
	Optical	7.4	22.8	14.7
10	X-Band	23.2	62	11.3
	Ka-Band	22.55	46	12.1
	Optical	9	30	15.4

The Figures (2a -2.c) show the (normalized) cumulative costs for a sequence of up to twenty Mars missions with identical telecom requirements following the assumptions outlined earlier. Three traces are shown for the optical channel, each corresponding to a different Operations Scenario (and ground receiving invest ment). The least expensive, assumes single-site reception with a cloud coverage that allows about 70% availability of real-time contact on any given day. The intermediate trace adds three-site diversity at a single longitude, raising contact assurance to above 95%, while the most expensive pathway represents world-wide coverage with high (> 99%) contact assurance.

As long as single-site reception can be assumed to be adequate, either of the new technologies (Ka and Optical) showa cross-over in the cost profile at a relatively modest number of Mars missions. If more missions are flown, the new technology begins to accrue a cost savings over the reference technology. The growth rate for these cost savings can be seen in the differences which appear in Figure (3) which shows separately the (normalized) cost of the first flight and each following flight for the three data volumes and each of the three technologies. The first flight costs for Ka-band and Optical include development of a single ground receiving site.

The improvement in value with added missions is most apparent with the Optical technology, where a substantial start-up cost for designing the first flight terminal and establishing the ground terminal is soon recovered by way of a significantly smaller replication cost for the subsequent flight terminals. This is true at all data volumes, and most significantly so at the highest data volume, where the recurring benefit is almost 3/4 units per mission with respect to X-band. Comparing the two RF bands, the difference between X- band and Ka-band is too close to call at the lowest data volume, where costs are dominated by fixed elements which do not vary with link capability. Only at the 10 Gb/day level does the recurring cost benefit of Ka-band (vs. X-band) become significant

3.1 a DSN Operations Cost Sensitivity

As was discussed above, price of a DSN service hour could conceivably vary over a range from a high, equivalent to the current reimbursable price, to as low as half that if the current efforts toward cost efficiencies are extremely successful. For the reference case (above), a value equal to the middle of this possible range has been used. Overall this sensitivity appears quite small and not an item of consideration.

3.1 b Optical Operations Cost Sensitivity

One of the assumptions made to establish an operating price for the Optical ground terminal was that a substantial number of missions existed which would share the usc of the operating hours of the station and hence share its annual recurring cost. This assumption can be relaxed without significant impact to the conclusion s being drawn. in the extreme case, we assume that the Mars missions being considered arc the only customers for the optical ground terminal(s), and that the full 6-month operating cost of sustaining and operating the ground terminal is borne by its lone customer, irrespective of the actual number of support hours required. Even if the Mars mission series must support by itself the full Operations costs for the Optical ground terminal, the break-even point for the optical technology still occurs at a modest number of missions at all data volumes.

3.2. **Spacecraft Power Sharing Sensitivity**

One of the assumptions made to size and cost the flight terminal is that power needed by the telecom subsystem is provided by a dedicated portion of the power subsystem. The mass and cost factors of this portion became part of the telecom burden. Different cost factors would exist if power were "free" to telecom because the power subsystem were sized to accommodate a power-hungry instrument which never ran concur-tent with telecom. Under this scenario, Ka-band becomes break-even with X-band because its main advantage, more effective usc of downlink power, is disarmed by the availability of free power. Optical continues to enjoy the advantage provided from a lower estimated replication cost for the flight terminal.

3.3. Flight Terminal Cost Sensitivity

Even more than the physical parameters, the estimated cost of replication of the various design flight terminals is subject to uncertainty. This can be driven by market forces, by unpleasant surprises in transition from engineering model to flight unit, or by technological progress which ripples through a design. The RF telecom designers estimated a probable uncertainty of up to 15% for either X- or Ka-band terminals. Because of the amount of common elements, the differential uncertainty between the two RF bands is thought to be well less than 10%. There is no comparable estimate for the uncertainty of the cost of the Optical flight terminal, so a value of 20% is assumed as a working figure, based upon the consistency between the basic estimates and modeled values for the optical units. These values were used to calculate the effect of variation in the flight terminal fabrication cost on the bre,ak-even point which can shift by -20% to 35% from the values shown in Fig. (2a-at).

3.4 Data **Storage Cost Sensitivity**

Onc basic assumption made throughout this study has been that adequate storage existed onboard the spacecraft that no data would be lost due to unavailability of planned contact. Such data would simply be stored and replayed at the next convenient opportunity. The two RF bands and the optical channel behave somewhat differently in this regard. The link designs for both RF bands have been set for a 95% confidence of real-time data delivery. The overall confidence of data delivery can be driven as small as desired by providing data storage to cover the 5% risk that real-time delivery does not succeed. By contrast, the cloud blockage hazard for the optical channel allows only a 70% confidence of real-time data delivery. In order to achieve the same overall reliability as the RF channel, an extra storage capacity equal to two clays data would be required.

The parameters defining the data storage have been based on those for Ncw Millennium Spacecraft.[7] The storage modules are based on commercial parts which hold about 0.5 Gbit, consume 0.25 W power and O. 1 kg mass An additional 2 W at-c consumed by a module which is read/write active. Two days data storage at 10 Gb/day would take nominally 40 modules, 4 kg, and 12 W total. For 1 Gbit/day, these figures drop to 4 modules at 0.4 kg and 3 W, and scale to 0.4 modules at 0.9 watts for 0.1 Gbit/day. The effect of this charging is negligible at 0.1 or 1.0 Gb/day, but extends the break-even point in number-of-missions for optical by 1.6 (vs. X-band) and by 2.8 (vs. Ka-band) at 10.0 Gb/day.

4.0 OPTICAL 3.5 m RECEIVING TERMINAL

Part 1 of this report included the development of an alternative link design for achieving, 10.0 Gb/day by way of a 3.5 m receive terminal combined with a 35 cm, 2.3 W flight terminal. The data volume was achieved through a combination of higher power on the spacecraft, higher precision collecting surface and use of three (rather than one) ground sites, allowing longer contact time. Even though the 3.5 m ground terminal is less expensive than the 10 m terminal, the need to build three instead of one extends the time to break-even to more than twice that of the basic sirlglc-site 10 m design for the 10.0 Gb/day case.

No specific link design was done for achieving the O. I or 1.0 Gb/day volumes with the 3.5m but a suitable configuration can be derived from the existing building blocks. in daytime reception, the ground terminal sensitivity is background light limited, and the more precise surface of the 3.5m terminal allows it to operate with a sensitivity which is about one-third that of the 10m photon bucket. Given that the 10 cm, 0.45W, flight terminal working with the 10m receiving system can transfer 0.1 Gb/day using about a 2 hour pass, that same flight terminal with the 3.5m receiving system should be capable of O. 1Gb/day in less than 8 hours. Similarly building upon the link design for the 1.0 Gb/day, which uses the 15 cm, 0.69W, flight terminal with the 10m receiver, an alternative design with the 25 cm, 1.35W, flight terminal and the 3.5m receiving system should achieve more than 1.0 Gb/day with a single 8 hour pass

interestingly enough, the 3.5111 receive system pays off sooner with the smaller data volumes than it does at 10 Gb/day where it was initially targeted. The delayed payoff for the largest data volume results from the need for three rather than a single ground terminal.

5.0 DSN 70 m RECEPTION

The DSN's 70 meter antennas offer a reception capability which is significantly more sensitive than that of the 34 m chosen for this study. If the 70 m is used instead, that additional sensitivity could reduce the mass and power consumption on the spacecraft. The impact of this can be seen by way of the spacecraft aggregate mass metric as defined earlier, which is displayed in Fig. (4) for the three data volumes, three channel bands and both the 34 m and 70 m antennas. The 34 m and optical channel data in this figure duplicates that displayed in Fig. (1), but is included here for direct comparison. As can be seen from the figure, the use of 70 m (vs. 34 m) for the 10 Gb/day data volume can result in a spacecraft aggregate mass reduction by 30% at X-band and by 23% at Ka-band. This benefit disappears for the low data volume of O. 1Gb/day whine there is almost no difference in the aggregate mass metric for either frequency band or receiving antenna.

The perspective changes when the overall cost is considered. For reference, the reimbursable price for DSN 70 m support to NASA missions is 2.5 times that for the 34 m. It seems reasonable to assume that this factor is appropriate for also scaling the net cost of six months tracking support to the Mars missions. Considering this, the aggregate cost for the 10 Gb/day mission with 70m support is approximately equal that with 34 m support, for either X- band or Ka-band. For the lesser data volumes, the aggregate cost with 70 m support exceeds that with 34 m support. The value of the 70 m lies in its ability to provide effective communications in more adverse situations, e.g. at greater distances than the Martian 2.7 AU, or at higher data volumes for targets at Mars range.

6. REAL-TIME LINK AVAILABILITY

The preceding comparisons all assumed a requirement for an average daily data return volume but did not specifically require that the link be available for connection at any particular instant of time. Onboard storage is assumed to be adequate to permit use of only one ground site and to provide buffering of the data to cover periods when the site is not in view or when contact with the site is blocked due to inclement weather. Past missions have had the luxury of "DSN (X-band) contact on demand" with a 95% confidence at any time during the day or night. Future missions are expected to have increased intelligence and, for cost-savings reasons, rely on much less link connection guarantees. Nevertheless, it is informative to consider what would be required to provide similar "guaranteed availability" using the new wavelength bands. Accommodating such contact at the new bands can be done with increased implementation and operations costs. Doing so would, of course, reduce the need for on-board storage.

Two coverage scenarios will be considered. The first assumes that only a single daily pass is required but that 95% "real-time" availability is required during that pass For the X and Ka-band systems, no change is needed as such availability is already extant within the current DSN link designs. For the optical wavelength, sinee site weather outages can occur on the order of 30% of the time, a total of three spatial ly-separated and simultaneously-visible (geometrically) sites would be required to provide the same real-time availability. This could be achieved by the implementation of a thin-station network within the continental USA and Hawaii, with corresponding development costs of 3 normalized cost units. Referring to Fig. (2a-2 c), the cost trace identified as " Optical-US Regional Net." corresponds to this high real-time availability scenarios.

The other scenario would require 24-hour (95% confidence) link availability to any specific mission. At present, only the X-band network provides that capability. Making the Ka-band system available world-wide in the 34-meter network costs an additional 0.8 normalized units, plus a small operations cost increment that would probably disappear within the overall DSN Operations budget. ***Providing*** optical with world-wide availability requires implementation of an international network of at least seven linearly-dispersed sites, for a normalized development costs of about 20 units. Other configurations are possible but at higher cost. [8]. Protecting high-confidence service requires scheduling (and charging for) three concurrently visible sites within the network configuration. The assured availability of contact eliminates the discounting of returned data volume and allows the actual scheduled time to be reduced by about 30%. Referring to Fig. (2a-2 c), the cost tram identified as " Optical-World-Wide." corresponds to this real-time availability scenarios.

The added requirements for high availability "on demand" do not fit well with the new higher-frequency technologies. The greater performance obtained in a buffered single-site mode comes with the acceptance of the higher weather hazard. Asking the missions to provide service in the "old-style", i.e. with guaranteed high link availability, significantly erodes their economic value. Nevertheless, even in these more extreme cases, the earlier mentioned benefits of smaller size, mass, etc. may still provide adequate benefit to the missions for their use.

Actually, there are some adjustments that could be made to these values. Recall that the spacecraft terminal designs for the optical wavelength were based on a single pass (expected) daily data volume using a single station. To account for weather outages, a higher clc,ar-weather data rate capability was provided which, upon discounting for the weather availability, resulted in the required data volume. Now, if there is a guaranteed availability (due to spatial diversity), there is no need to design for the higher data rate. This can be adjusted by reducing either the required contact time or laser power or aperture size; any of which will reduce (slightly) the cost involved. The displayed values were calculated with the assumption that a reduced contact time was used to adjust the capacity, but the alternative of redesign of the flight terminal have resulted in lesser cost and thus quickly payback for the optical. This trade has not been examined.

Alternatively, if three simultaneously-visible (geometrically) sites are required to "ensure" availability, then for approximately 44% of the time two of them are in clear weather and could be supporting separate missions. Additionally, 34% of the time, all three would be available for separate mission support. Since the clear weather state cannot be predicted as far in advance as scheduling of support is done, these stations would have to be offered at a lesser grade of service (and lower " price") than that resulting from the weather unavailability alone. Revenues (if any) from marketing this lesser grade of service would be used to reduce the price of the top quality service. Due to time limitations in this study, these factors were not considered.

7. CONSIDERING OTHER DESTINATIONS

The initial formulation of the study included three separate destinations: one at Mars to serve as an archetype for the nearby planetary targets, one at Neptune representing the far Outer Planets, and one in the Earth-Lunar neighborhood. Telecom aspects of the Neptune case have been largely developed as an extrapolation from the Mars case. Overall economic aspects depend strongly upon the telecom requirements for power and mass (and cost of transporting that mass). The cross-impact of these factors upon the telecom function is explored in the following.

7.1 Power

Power to run the spacecraft designed for Mars is provided by Solar-PhotoVoltaic panels. Radiant energy from the sun disperses much like the communications signal does, so that the solar energy flux declines inversely as the square of the distance from the Sun. Efficiency factors will further complicate this relationship. While solar panels work well at Mars orbit (approx. 1.4 AU), the performance falloff is such that the practical choice for power source at Jupiter (5 AU) and beyond is RTGs (Radio-isotope, Thermo-nuclear Generators). But RTGs are an expensive source of spacecraft power. A current working figure is almost twenty times the cost of power in Mars orbit. [9]

7.2. **Transportation**

Putting a spacecraft into orbit at Neptune requires substantially more expenditure of energy than would be needed at Mars, and hence requires either a larger launch vehicle or tighter constraint on the mass of the spacecraft itself. Either pathway increases the net cost per kg for transporting a specified mass to

Mars orbit. The specific value is dependent upon details of trajectory, and appears to be about four times the transportation cost for Mars

7.3. **Balance of Power vs. Aperture (Mare)**
Since moving to the Outer Planets significantly changes the relative cost of power and mass delivered to the planetary destination, telecom designs which were reasonably well balanced economically for Mars will likely not be well balanced at Neptune. With power as the apparently more expensive resource, savings can be found by increasing the transmitting aperture (and its mass) while decreasing the transmitted power, maintaining the effective radiated power constant. However, increasing the aperture also increases the downlink pointing losses and/or requires more precision from the attitude control system. To the extent that re-balancing is desirable, its effect will show best via the unified metric for aggregate cost of the telecom, including its cross-impacts on other spacecraft systems.

A bar-chart for aggregate cost of telecom in Neptune orbit appears as Fig. (5), for the range of data volumes achievable by the link configurations designed for Mars. As indicated, the volume is reduced by the factor of 0.008 from the Mars capability. Two alternative flight terminal designs are also indicated for the 34 m X-band cases where the higher cost of power at Neptune gives substantial cost reduction for re-balancing power vs. mass The two (34 m) alternatives shown are for approximately doubled antenna area ancl halved downlink power, with the 80 Mb/day obtained via a 2.7 m antenna and a 22 W transmitter, and the 8 Mb/day obtained via the 2.0m antenna and a 4W power amplifier. The 2.7 m antenna is assumed to be consistent with the family of smaller antennas in design/fabrication cost and mass and would be the maximum allowed by the Delta launch vehicle. The added non-recurring costs for the redesign are included in the figures. Similar alternatives were examined for the other RF configurations but in all such cases, the increment to non-recurring costs absorbed any savings available through reduction in power subsystem costs.

Use of the DSN's 70 m antenna can reduce the spacecraft resources needed for a specified data volume. While this did not permit significant savings for the Mars case, the increased costs of power and mass at Neptune favor the use of the 70 m antenna for the larger data volumes. The revision to the flight terminal designs for transmission to the 70m antenna was described in Section 11.2.3 of our Part- I report [2]. The corresponding aggregate costs are shown in Fig. (5) for 70 m X-band at 8.0 and 80.0 Mb/day and for 70 m Ka-band at 80.0 Mb/day. The added non-recurring costs for the redesign are indicated in the figures. The 70 m Ka-band value includes an allowance for an array feed or other complex receiving/compensation system.

8. CON CLUDING DISCUSSION

In this "Part 11" report of the study, two critical metrics for comparing the benefits of utilizing X-band, Ka-band and optical frequencies for supporting generic classes of Martian exploration missions have been evaluated. These two metrics (spacecraft communications system mass and total end-to-end NASA cost) are among the most important metrics to the potential "customers" for the communications technologies.

The mass metrics show that use of higher frequencies uniformly results in less overall mass on the Mars spacecraft. At the 0.1 Gb/day volume the improvement is modest, with Ka-band 7% and Optical 28% less than the X-band systems, respectively. At 1.0 Gb/day volumes, the savings become more significant (22% and 44% respectively for Ka and optical relative to X). The largest savings occurs at the largest 10 Gb/day data volume where a 25% mass savings results from Ka-band and a 51 % for Optical (relative again to X-band).

For the optical technology, there is an initial cost investment required (almost three cost units for a single receiving site). However, the cost slope is significantly smaller than the slopes of either the X-band and Ka-band technologies (in all data volume cases), so that after a modest number of missions the investment begins to pay significant savings dividends. This nominal cross-over point for a series of Mars missions is as small as 5.0 missions (at the 10 Gb/day case when compared to X-band) and increases only to 8.2 missions (when comparing Optical with either X-band or Ka-band at the 0.1 Gb/day volume). The actual values can shift by -20% to 35% when reasonable parameter variations are considered. A significant factor in this smaller slope is the lower replication cost of the optical flight terminal. For any of the flight terminal types, replication cost can be modified by a variety of factors including technology investments, acquisition strategy and conditions of the external marketplace for the same or similar devices. The current study assumed near-term technology without significant external forces, and one-at-a-time acquisition. Technology efforts currently underway at JPL and elsewhere should both reduce the terminal's costs and add uncertainty to the differences seen here,

Choosing Neptune as an alternative destination for the telecom configurations as designed for Mars enhances the value of either Ka-band or optical communications technology relative to the baselined X-band capability. Configurations which would deliver 10 Gb/day at Mars should allow for 80 Mb/day at Neptune, but at substantially higher cost due to higher cost of transportation and power. Some redesign is appropriate, including selective use of the DSN 70 m antennas. Assuming that single-site ground receiving capability is separately provided, recurring mission savings on the order of 15% (for 34 m Ka-band) to 30% (for optical or 70m Ka-band) are available at this data volume, compared to a reference design for 70 m X-band. The cost differential declines substantially for the smallest (0.8 Mb/day) configuration.

The comparisons performed in this report have concentrated on the areas of equivalent spacecraft terminal mass and total end-to-end NASA cost 1 lowever, different missions may have different constraints or emphasize the importance of different parameter values. Size, for example was not specifically bookkept nor was there established any equivalent benefit metric for size reduction. For the X-band and Ka-band systems the sizes are very similar. For Optical, there is a significant reduction in system size (10-30 cm telescope diameters vs. 1-2 meter diameter antennas). Smaller size can result in potentially smaller spacecraft support structures and may even permit, in some cases, a smaller class of launch vehicles.

Additionally, there are other potential benefits, as well as liabilities associated with changing communications wavelengths Changes from X- to Ka-band can enhance or degrade the ability to extract certain radio science observables. For example, the development of Ka-band equipment for Cassini spacecraft is being done explicitly to enhance the potential for Radio Science detection of gravitation waves. Changing from RF to Optical means giving up radio science all together, although it can be replaced by a whole new (as yet undefined) area of optical "light science". Additionally, there are developments underway that could combine the imaging camera (flown on most space missions) with the optical communications capability. This would significantly reduce the mass of the combined telecom and science imaging functions. Finally, there are spectrum crowding issues facing deep-space communications in the future that could force movements to the higher frequency bands. Time did not permit any of these issues to be explored.

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ACKNOWLEDGMENTS:

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. The authors are indebted to P. Estabrook and C. Edwards, and many others at JPL for stimulating and fruitful discussions

Fig 1

Cost for First Flight & Repeat Flights

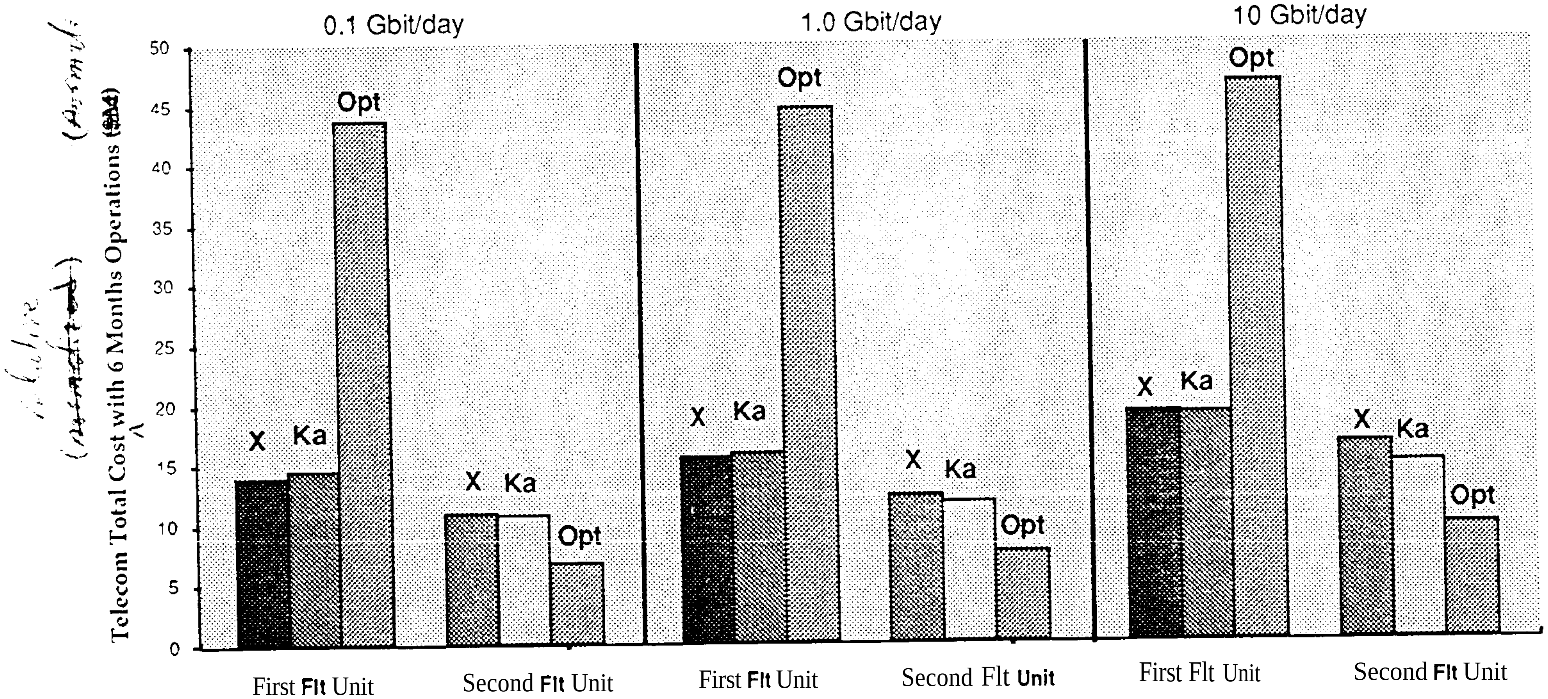


Fig 2a

Cumulative Costs at 0.1 Gb/day for up to 20 Flights

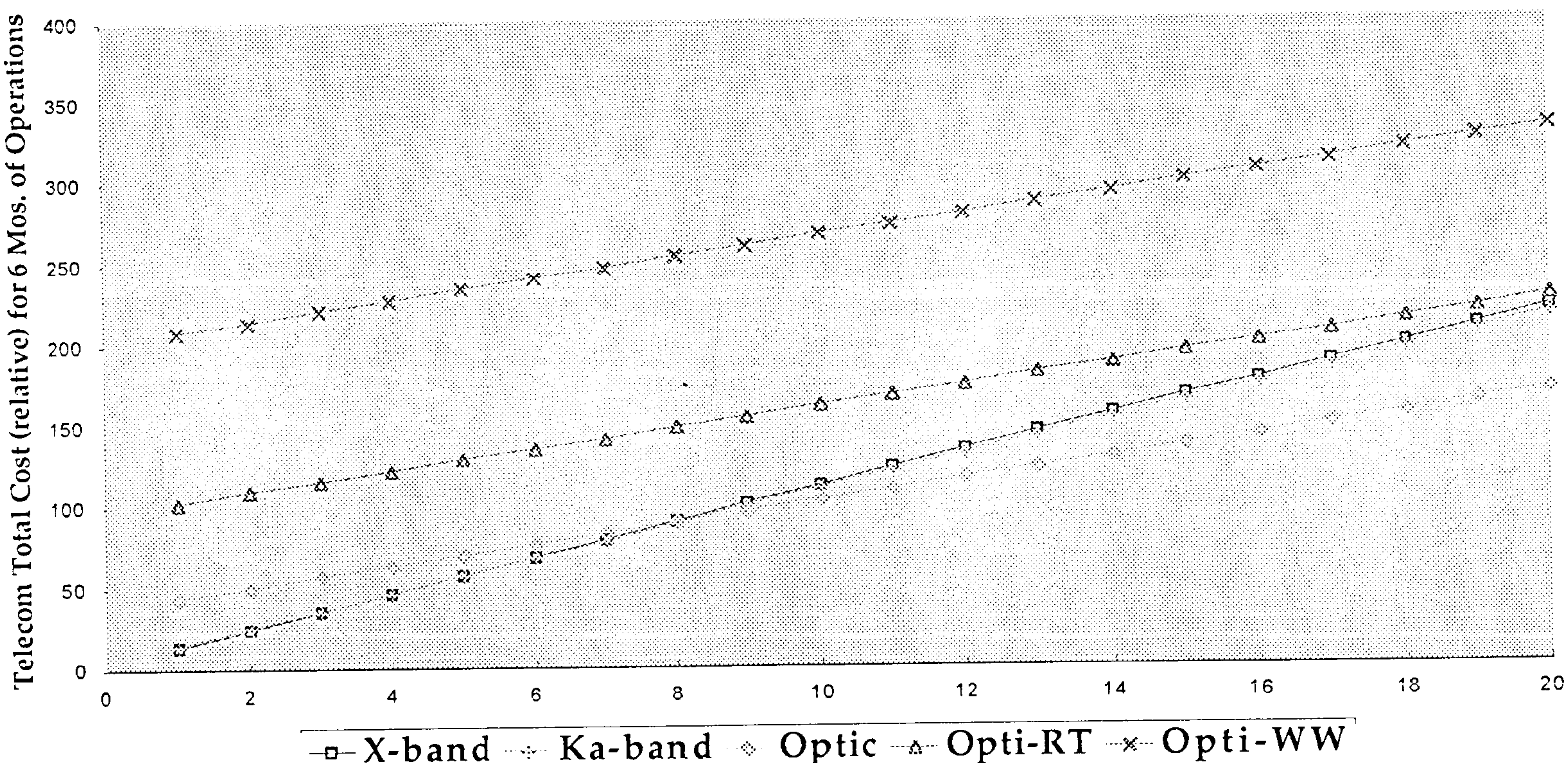


Fig 2b

Cumulative Costs at 1.0 Gb/day for up to 20 Flights

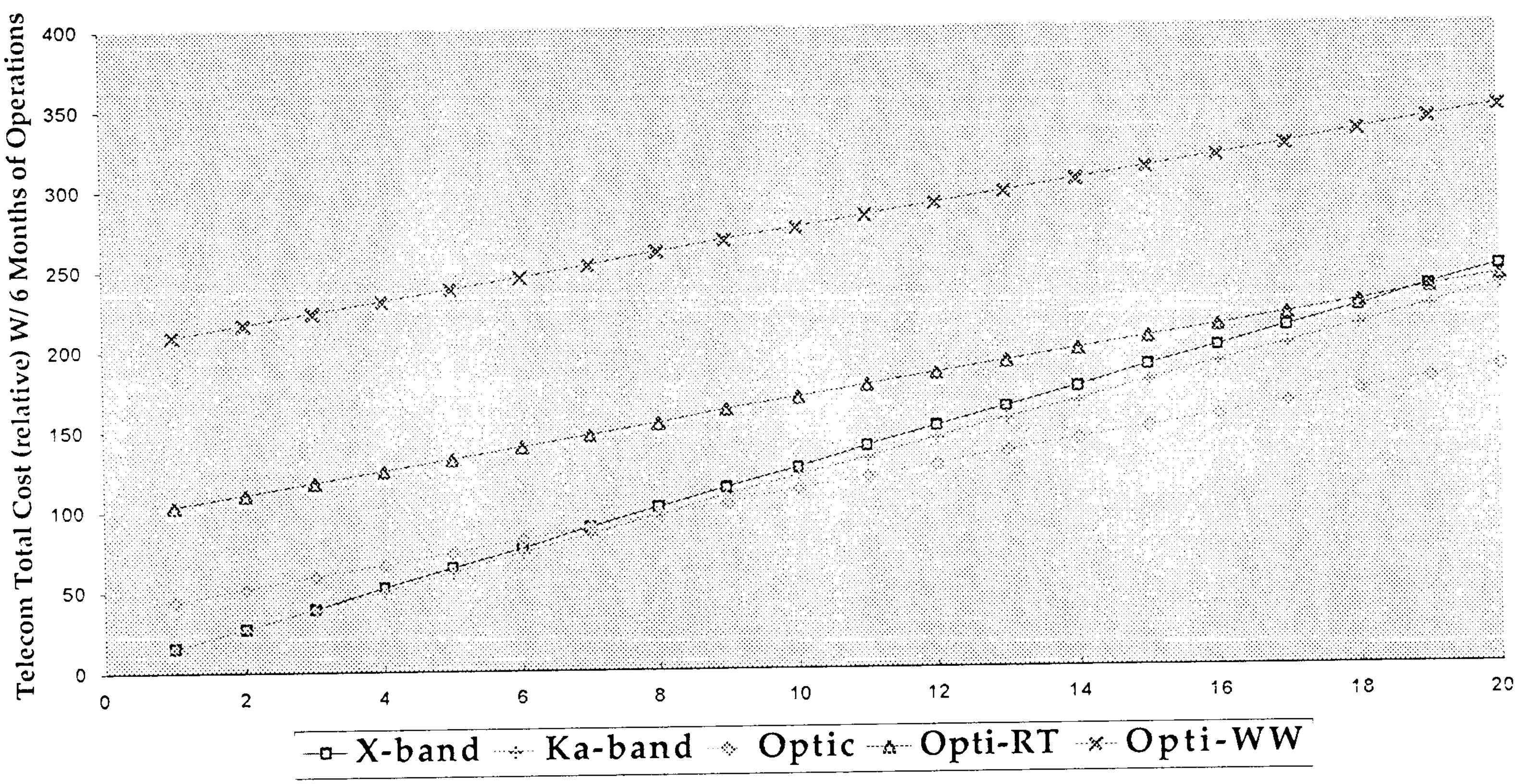


Fig 2c

Cumulative Costs at 10.0 Gb/day for up to 20 Flights

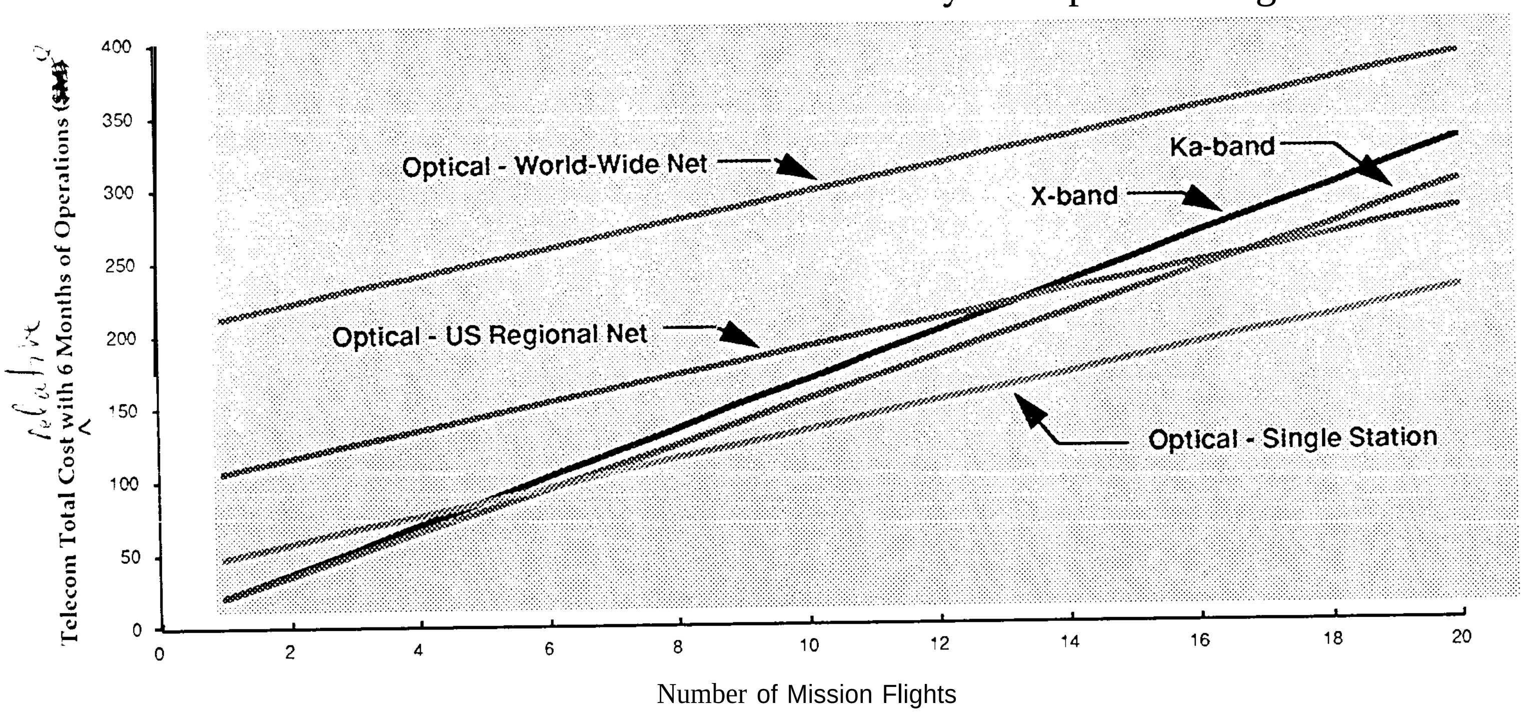


Fig 3

Cost for First Flight & Repeat Flights

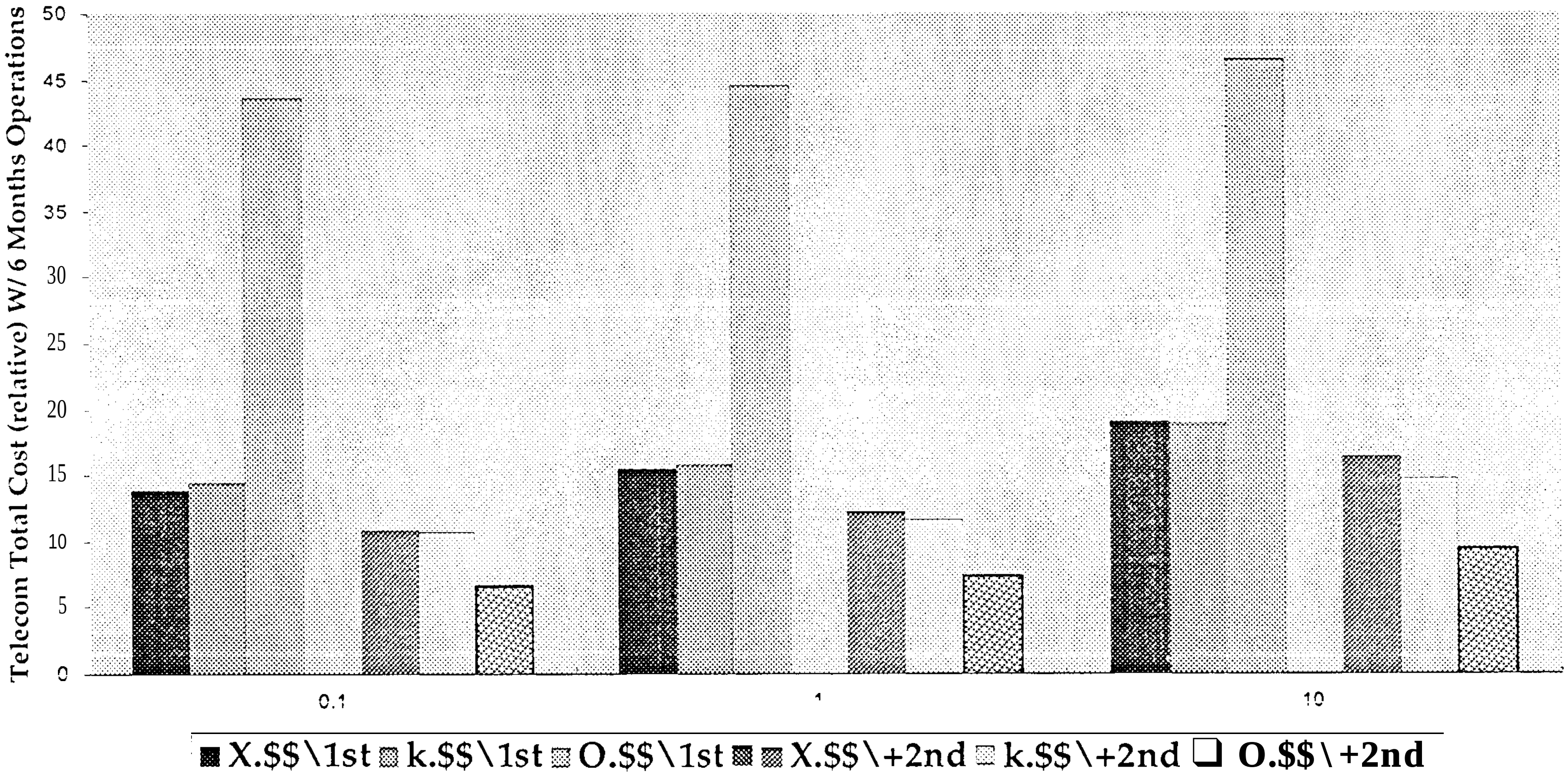
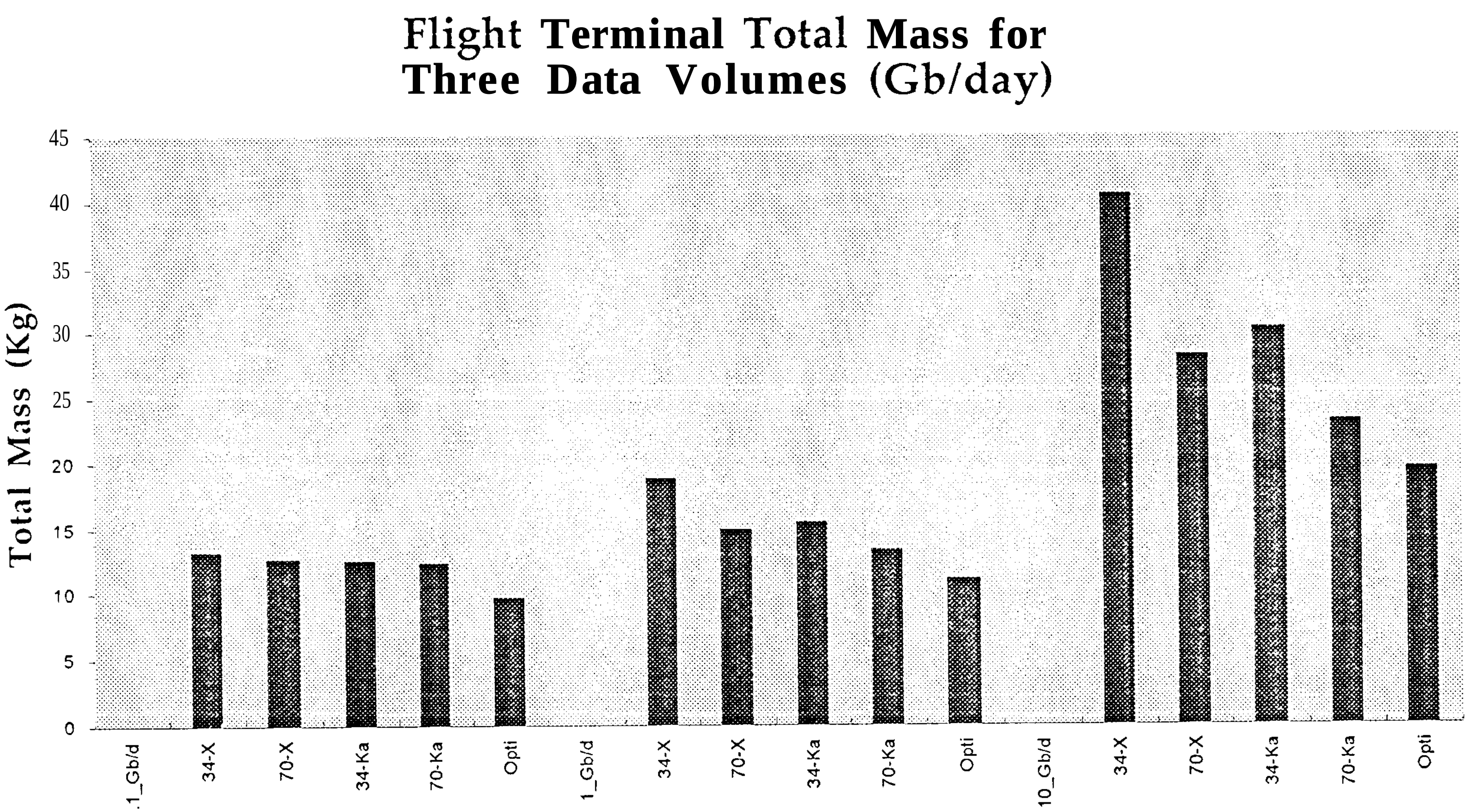


Fig 4

JPL



Flight Terminal Total Mass for
Three Data Volumes (Gb/day)
Total Mass (Kg)
45
40
35
30
25
20
15
10
5
0
.1_Gb/d
34-X
70-X
34-Ka
70-Ka
Opti
1_Gb/d
34-X
70-X
34-Ka
70-Ka
Opti
10_Gb/d
34-X
70-X
34-Ka
70-Ka
Opti

Fig 5

Aggregate Cost for Neptune Mission at Three Data Volumes (Mb/day)